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Palaeo-lake and Swamp Stratigraphic Records of Holocene Vegetation and Sea-level Changes, Mangaia, Cook Islands[1]

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ABSTRACT: Stratigraphy of swamps inside the inner makatea rim of Mangaia was investigated to show Holocene changes in vegetation and sea level. In the mid-Holocene five lakes existed where there are now clay-filled swamps, and lake notches on the makatea wall indicate that sea level was sustained at 1.1 m higher than present. Fine annual laminations in gyttja deposits indicate the greatest lake depth in that period, dated between 6500 and 4500 yr B.P. Pollen evidence of wetland communities also points to a higher sea level at that time. Pollen analyses and charcoal concentrations of cores from two different drainage basins show that the greatest change in terrestrial vegetation of the Holocene on Mangaia was clearance of forest by people, resulting in soil erosion from the inner volcanic cone and clay infilling of the lakes. Humans were present on Mangaia as early as 2500 yr B.P. Although some clearance of forest occurred during that early period of human occupation, systematic island-wide anthropogenic disturbance began ca. 1650 yr B.P., as shown in both cores from a decline in forest pollen and a major and sustained increase in *Dicranopteris*, a fern that colonizes disturbed land.

MANGAIA IS THE second largest and most southerly of the Cook Islands (21° 54′ S, 157° 58′ W), with a land area of 52 km^2 (Figure 1). The island can be divided into two concentric geological zones. The inner zone is a subdued basaltic volcanic cone to 168 m, flattened at the summit possibly by marine erosion before its uplift (Wood 1967), dating between 17 and 19 million yr B.P. (before present) (Dalrymple et al. 1975). The outer zone is a complete raised limestone rim or makatea, 0.7 to 2 km wide, to 70 m, with erosional topography of steep terraces on the outer edge and cliffs on the inner edge (Stoddart et al. 1985).

These two zones currently support contrasting vegetation. The makatea is covered by forest, dominated by *Barringtonia asiatica* (L.) Kurz, *Pandanus tectorius* Parkinson, *Cocos nucifera* L., *Hernandia moerenhoutiana* Guillemin, and *Elaeocarpus tonganus* Burkill (Merlin 1991, Franklin and Merlin 1992), and an understory dominated by *Asplenium nidus* L. and other ferns. Scientific names in this paper follow Whistler (1990). Much of the central volcanic hill is covered by the fern *Dicranopteris linearis* (Burm. f.) and scrub *Pandanus tectorius*, *Dodonea viscosa* Jacq., and *Casuarina equisetifolia* L. River valleys are lined by the ferns *Cyathea* sp. and *Angiopteris longifolia* Grev. & Hook with an upper story of *Hibiscus tiliaceus* L. and scattered *Inocarpus fagifer* (Parkinson) Fosberg.

Mangaia receives a mean annual rainfall of 1967 mm, with a range of 1024 to 2983 mm in the period 1914–1984 (Thompson 1986). There is a pronounced wet season from November to April, and a dry season from May to October. Drainage is radial, with deeply incised first- and second-order streams off the central cone feeding lowland swamps collected against the inner makatea cliff. There are seven major swamp areas, shown in Figure 1, separated by low basaltic ridges: Veitatei,

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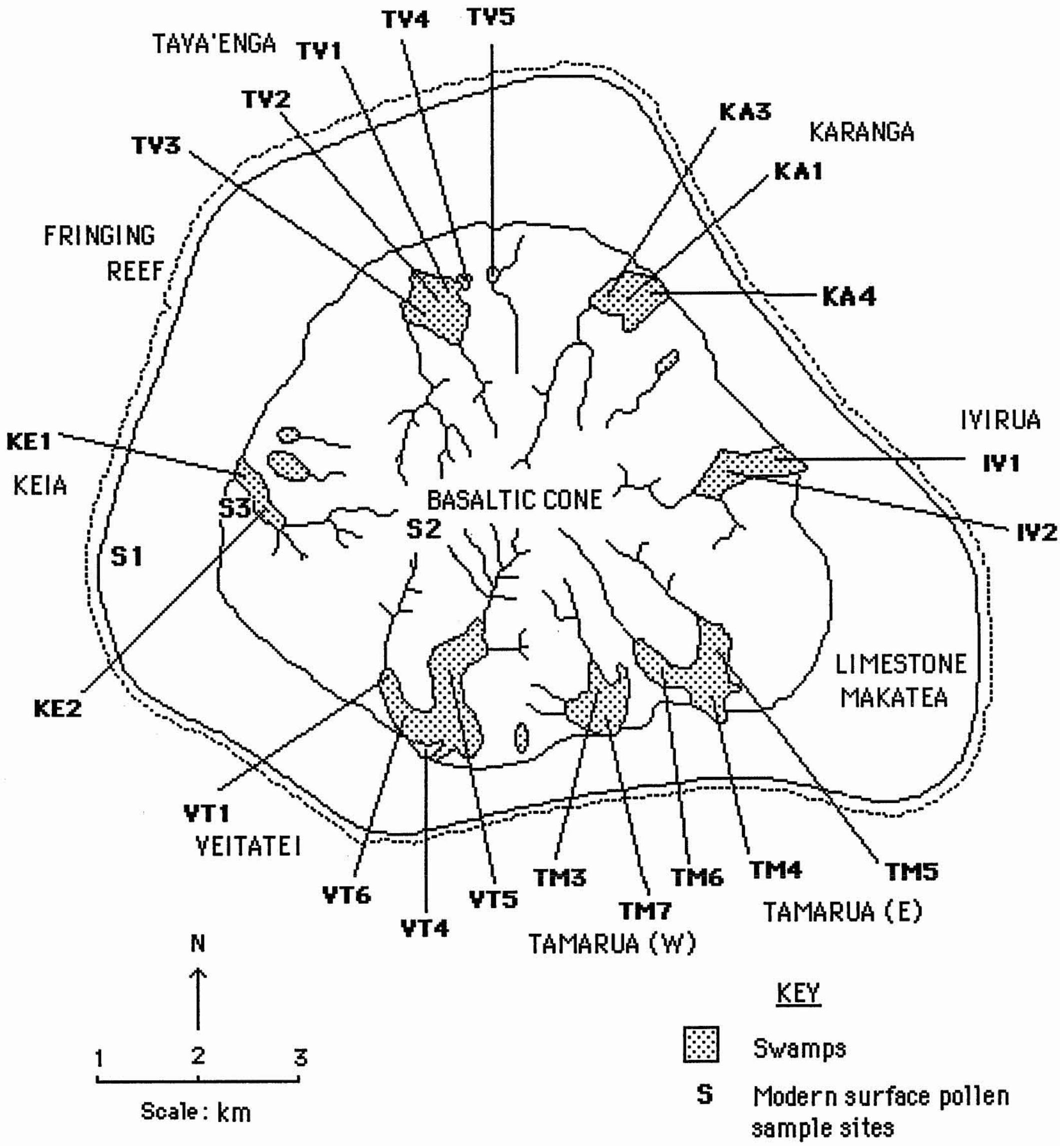


FIGURE 1. Map of Mangaia, showing seven major swamp areas situated against the inner makatea edge and locations of core sites.

Tamarua (W), Tamarua (E), Ivirua, Karanga, Tava'enga, and Keia. At the lowest outer edges water collects and sinks beneath the makatea limestone in radially draining cave systems (Ellison in press), and at that point the swamps are 1 to 6 m above sea level, except Keia and Tava'enga, which are 20 to 30 m above sea level.

During the mid-Holocene a higher sea level stand occurred, indicated by raised coral microatolls on the NW shore, reaching +1.3 m 5000 yr B.P. and a maximum level of +1.7 m 4000–3400 yr B.P., and probably exceeded the current level until 2900 yr B.P. (Yonekura et al. 1988). Subsequently, the island was settled by Polynesians, who cleared vegetation from the inner volcanic cone, reduced or eliminated certain species of plants and animals, introduced other species of nonnative plants and animals, and utilized the swamps for taro cultivation (Steadman and Kirch 1990, Kirch et al. 1991, 1992).

The purpose of this study was to investigate these Holocene events in the sedimentary and palynological record of the swamps of Mangaia. This was part of an interdisciplinary effort to investigate human impacts on island ecosystems. Patterns of sedimentation and pollen deposition are subject to local conditions, hence interpretation of these islandwide events requires a comparison of the records from several swamps. In an earlier study, Lamont (1990) and Kirch et al. (1992) obtained a 15-m core dated to 6000 yr B.P. from Lake Tiriara in Veitatei and analyzed 50 cm subsamples and 150 pollen/spore identifications at each level to give results in relative proportions. This research indicates forest domination (with a disturbance event at 6100 yr B.P.) until a wetter period ca. 3700 yr B.P., and a further decline in forest after 1600 yr B.P. to *Dicranopteris* (=*Gleichenia*) and *Acrostichum* ferns. These results suggest that the early Polynesians caused major environmental disruption early in their settlement, as has been shown for Hawaii, Easter Island, and Fiji (Kirch 1982, Flenley and King 1984, Southern 1986, Bayliss-Smith et al. 1988). Confirmation of this record from Mangaia was deemed possible by use of more intensive sampling and pollen concentration analysis in Veitatei and a second drainage basin (Benninghoff 1962). Sampling and dating key cores in all seven swamps would allow separation of the overall record of Holocene sea-level change and human catchment disturbance from local factors.

MATERIALS AND METHODS

In all seven swamps, wet irrigated taro, *Colocasia esculenta* (L.) Schott, farming begins where the stream valleys widen toward the base of the volcanic slope and continues toward the makatea, where these branches merge into one swamp basin (Allen 1971). At the lowest segment close to the cliff and conduit cave entrance, water ponds to form an area too wet for taro cultivation, which is occupied by the sedge *Scirpus subulatus* Vahl, or in the case of Veitatei, the open water of Lake Tiriara. This location, the center of the lowest end of each swamp, was selected to give a stratigraphic record representative of each drainage basin and comparable between drainage basins. Each swamp was cored at this lowest location, and comparative cores were taken from the centers of the upper valleys.

Cores were taken manually, using a 4-cm-diam., 1-m Livingstone corer, and a second 2-cm-diam., 50-cm Livingstone corer designed to penetrate clay. A 4-cm-diam., 50-cm Hiller corer was found to be of use in penetrating hard clay in the upper valley locations. For coring the lakes a raft was constructed from inflated inner tubes and a plywood board with a central hole. Core segments were extruded into spilt plastic tubes, stratigraphy was described, and sediment color determined using Munsell charts. Tubes were then sealed with tape. The corers were disassembled and washed clean for each core section.

Samples for dating were cut from sediment in the tubes and the outer surface scraped off, then wrapped in aluminum foil, and refrigerated. Samples were later submitted to Beta Analytic (University Branch, 4985 SW 74 Court, Miami, Florida 33155) for radiocarbon dating. Ages reported here are "conventional ^{14}C ages" as defined by Stuiver and Polach (1977). Calibration and probability estimates were made using Revision 2.0 of the "Calib" FORTRAN microcomputer program (Stuiver and Reimer 1986).

Two cores (TM7 and VT6) were selected for laboratory analysis. Core tubes were X-rayed, then subsampled for pollen anaysis and percentage organic matter determination. Sediment concentration for pollen analysis was by standard chemical treatments (Erdtman 1969, Faegri and Iverson 1975), and a known number of exotic *Lycopodium* spores were added for determination of absolute microfossil concentration (Benninghoff 1962). At least 200 fossil pollen and spores were identified on exclusive transects on each slide, and charcoal fragments were counted. Percentage organic content in sediment was determined by loss of dry weight on combustion at 500°C for 4 hr.

To generate a pollen reference collection, 70 flower samples were collected on Mangaia, and 11 in upland forest on Rarotonga, which could be analagous to former forest cover on upland Mangaia. Unknown plants were pressed and sent to Art Whistler at the University of Hawaii for identification. For pollen identification a key was created from a description of the reference collection, previous collections from Tonga (Ellison 1989), and use of relevant regional literature.

For an indication of relative pollen representation, five surface samples were collected from moss polsters in different vegetation assemblages: outer makatea forest, the central mountain summit, the edge of a taro swamp, and two from the upland forest of Rarotonga. The Mangaia locations are shown in Figure 1. At each site vegetation was surveyed along a 50-m transect around the moss polster to show percentage cover.

STRATIGRAPHIC RESULTS

The locations of cores are shown in Figure 1, the stratigraphy in Figure 2, and dating results in Table 1. In five drainage basins, Veitatei, Tamarua (W), Tamarua (E), Ivirua, and Karanga, a similar stratigraphy was discovered. The base was a dense green/gray clay (5Y 2.5/2), which was difficult to penetrate, and in core TM7 this basal clay was 6 to 11% organic. In some cores hard rock could be felt by knocking with the core column. The deepest core was IV1 at 11.6 m. Core VT4 from Lake Tiriara reached 11.5 m depth, but in both this core and the adjacent VT6 the basal clay was not reached. All other cores reached base.

Above the basal clay was a homogeneous and fine lake peat or gyttja of black color (10YR 2/1 or 10YR 3/2). Peat above this basal clay was dated in key cores of four drainage basins: 7260 ± 80 yr B.P. at 1090 cm depth in Ivirua (IV1), 7240 ± 100 yr B.P. at 835 cm depth in Tamarua (W) (TM7), 6730 ± 120 yr B.P. at 765 cm depth in Tamarua (E) (TM4), and 6450 ± 80 yr B.P. at 505 cm depth in Karanga (KA4). Because the Veitatei cores were not bottomed, a basal peat date could not be obtained. Full dating results are given in Table 1 and shown in Figure 2. In TM4 an orange, spongy peat occurred from 730 to 760 cm depth above the basal clay and below the black lake peat.

In several cores the deeper lake peat sequence is interrupted by clay bands. Two occur between 920 and 980 cm depth in IV1, and the interim peat was dated at 6500 ± 80 yr B.P. A clay band occurs at 640–650 cm depth in TM7, and peat immediately below this gave a date of 6480 ± 100 yr B.P.

X rays of core TM7 indicated layering in the peat between 665 and 455 cm depth. This commences above the clay band dated at 6480 ± 100 yr B.P., and the cessation of layering was dated at 4500 ± 90 yr B.P., which also coincides with a clay band. The laminations are 60–70% organic and occur approximately every millimeter. There are thicker layers at depths of 635, 620, 550, 540, 528, 495, 478, and 459 cm.

In two drainage basins, Tamarua (E) at 450 cm depth and Ivirua at 440 cm depth, the black lake peat is replaced by a red/brown reed peat (7.5YR 3/4 or 10YR 3/2). This was dated in TM4 to 4000 ± 70 yr B.P. Cores TM5 and TM6 from higher in the Tamarua (E) swamp showed this reed peat from 8 to 7 m depth. The same peat occurs higher in the TM7 core, between 2 and 1 m depth, and X rays showed strandlike reed blades in the peat.

Clay deposits occur above the peat sequences in all drainage basins. The reduced clay is dark gray (5Y 3/1) and turns red when dried in the laboratory. The deepest clay sequences occurred in the Veitatei basin, with 620 cm of clay above peat in core VT6 in the western branch of the swamp and 450 cm of clay above peat in core VT5 in the eastern branch of the swamp. However, no comparable clay deposit occurs in the lowest core in Lake Tiriara (TM4). The deepest clay at the lowest basin core location was 260 cm at Karanga (KA4), whereas Tamarua (W) and Ivirua had clay deposits as deep as 170 and 70

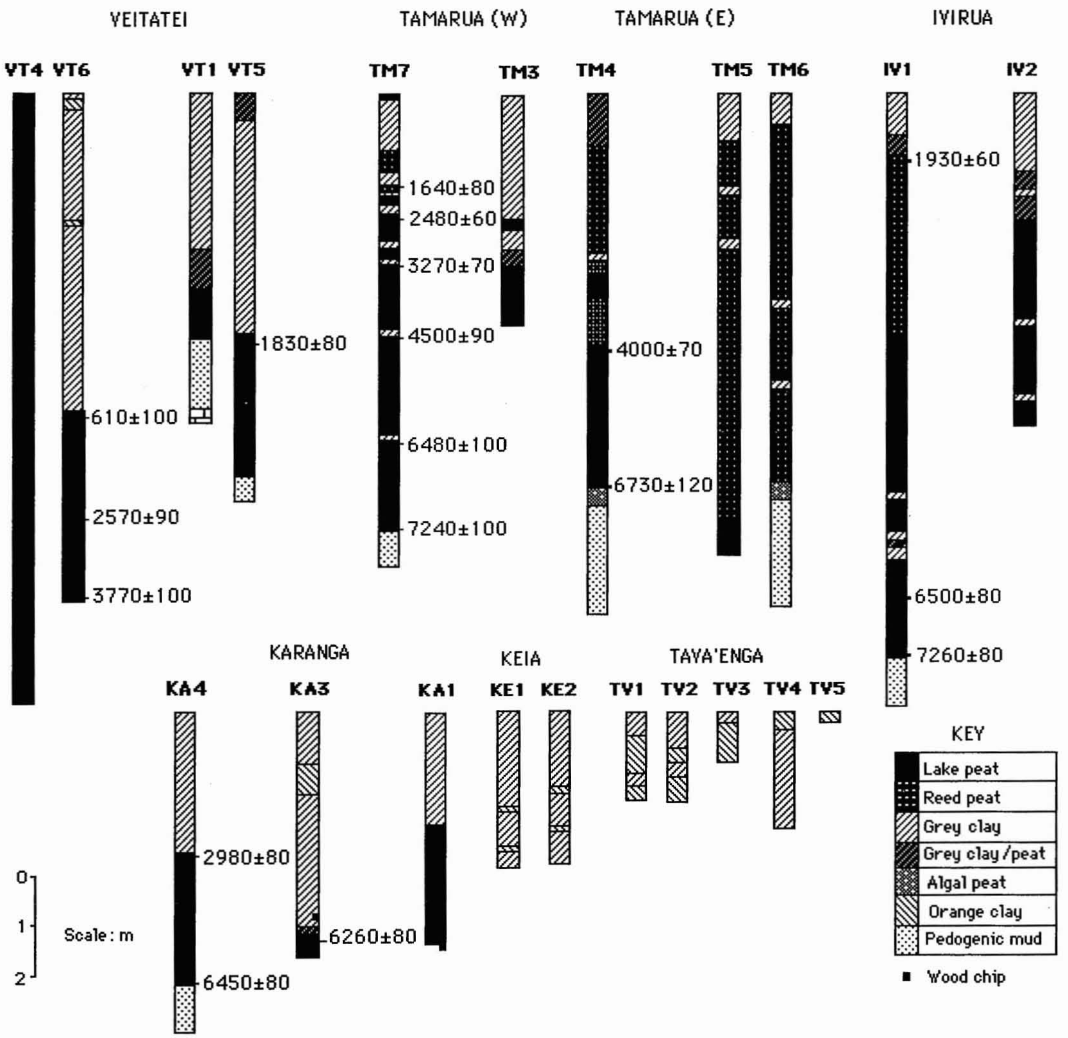


FIGURE 2. Stratigraphy and radiocarbon dates of the swamps of Mangaia, with lowest basin cores to the left of each group.

cm, respectively. In Tamarua (E) the 80-cm deposit is an organic/clay mix.

The commencement of deposition of clay over peat has been dated in seven cores; the dates are from peat immediately below the clay. The most anomalous is Karanga, with a date of 2960 ± 80 yr B.P. below 260 cm of clay, and higher in this swamp core KA3 gave a date of 6260 ± 80 yr B.P. below 390 cm of clay. Peat below clay gave dates of 1930 ± 60 yr B.P. in IV1, 1830 ± 80 yr B.P. in VT5, 1640 ± 80 yr B.P. in TM7, and 610 ± 100 yr B.P. in VT6. The most complex transition from peat to clay is in core TM7, with increasingly frequent clay bands from 320 cm depth, dated at 3270 ± 70 yr B.P., to 100 cm depth where the clay becomes continuous (Figure 2).

In two of the seven drainage basins only clay was found in all cores. In Keia clay was cored to 3 m in the lowest basin and to 2.8 m

TABLE 1

^{14}C DATES FROM STRATIGRAPHY ON MANGAIA

SAMPLE NO.	BETA NO.	DEPTH (cm)	UNCORRECTED ^{14}C	∂^{13}C	CONVENTIONAL ^{14}C AGE	CAL B.P.
TM7-1	47727	173–183	1720 ± 80	−29.7	1640 ± 80	1686 (1539) 1420
TM7-6	56330	225–235	2560 ± 60	−29.8	2480 ± 60	2736 (2709, 2633, 2605, 2587, 2541, 2535, 2499) 2371
TM7-2	47728	327–337	3330 ± 70	−28.3	3270 ± 70	3619 (3475) 3412
TM7-5	47731	450–460	4550 ± 90	−28.1	4500 ± 90	5305 (5256, 5184, 5126, 5112, 5083, 5061, 5059) 4985
TM7-3	47729	670–680	6510 ± 100	−26.3	6480 ± 100	7439 (7419, 7393, 7368) 7279
TM7-4	47730	830–840	7320 ± 100	−30.2	7240 ± 100	8119 (8037) 7929
VT2-1*	47732	630–640	610 ± 100	−25.2	610 ± 100	670 (638, 597, 566) 530
VT2-3*	52830	835–845	2570 ± 90	−25.3	2570 ± 90	2768 (2744) 2499)
VT2-5*	47733	990–1,000	3800 ± 100	−26.8	3770 ± 100	4400 (4147, 4100, 4098) 3988
VT5-1	47734	475–486	1900 ± 80	−28.9	1830 ± 80	1868 (1804, 1786, 1760) 1635
IV1-1	52829	120–130	1980 ± 60	−27.8	1930 ± 60	1943 (1878) 1826
IV1-2	47720	918–927	6580 ± 80	−29.6	6500 ± 80	7438 (7423, 7384, 7375) 7291
IV1-3	47721	1,085–1,100	7340 ± 80	−29.9	7260 ± 80	8122 (8044) 7946
KA4-1	47723	256–266	3020 ± 80	−27.5	2980 ± 80	3331 (3207, 3184, 3175) 3041
KA4-2	47724	500–508	6490 ± 80	−27.1	6450 ± 80	7430 (7327) 7197
KA3-1	47722	425–445	6320 ± 80	−28.4	6260 ± 80	7267 (7183) 7096
TM4-1	47725	493–499	4070 ± 70	−29.6	4000 ± 70	4550 (4513, 4490, 4448) 4412
TM4-2	47726	762–767	6790 ± 120	−28.9	6730 ± 120	7679 (7579) 7439

* NOTE: VT2 is a duplicate core to VT6.

higher in the swamp. Two red clay bands were found in both cores between 1.5 and 2.5 m depth. The cores were finished in hard clay. A similar sequence was found at Tava'enga, where two cores penetrated 1.7 m of clay, passing through a band of red clay and finishing in extremely hard red clay. The lakes near Tava'enga were similar. At the lower Lake Kauravai red clay was penetrated on the lake floor; 2.1 m of clay was cored until very dense gray clay was reached. The higher Lake Tepeuru Ngau rendered a 20-cm core of very dense clay. The hard clay at the base of these cores was very similar to the hard clay found at the base of the deep peat cores in other drainage basins, just above rock.

In five drainage basins a fossil water level notch was found on the makatea wall at the lowest margin of the swamp ca. 1 m above the current water level. This was measured by distance of indentation of the rock from a vertical, shown in Figure 3. Limestone formations are often undercut near sea level by "tidal" type marine notches (Pirazzoli 1986), which have been used on several Pacific islands to indicate higher sea-level stands (Bourrouilh-Le Jan 1985, Pirazzoli and Montaggioni 1988).

POLLEN ANALYSIS RESULTS

Modern Surface Pollen

Relative abundance diagrams of vegetation and pollen from each of the surface sample sites are plotted in Figure 4. Site 1 from the outer makatea forest has vegetation dominated by *Barringtonia asiatica*, which does not occur in the pollen assemblage, which rather is dominated by spores of *Asplenium nidus* and other spores. At site 2, the mountain summit, both the vegetation and pollen assemblages are dominated by *Dicranopteris linearis* and

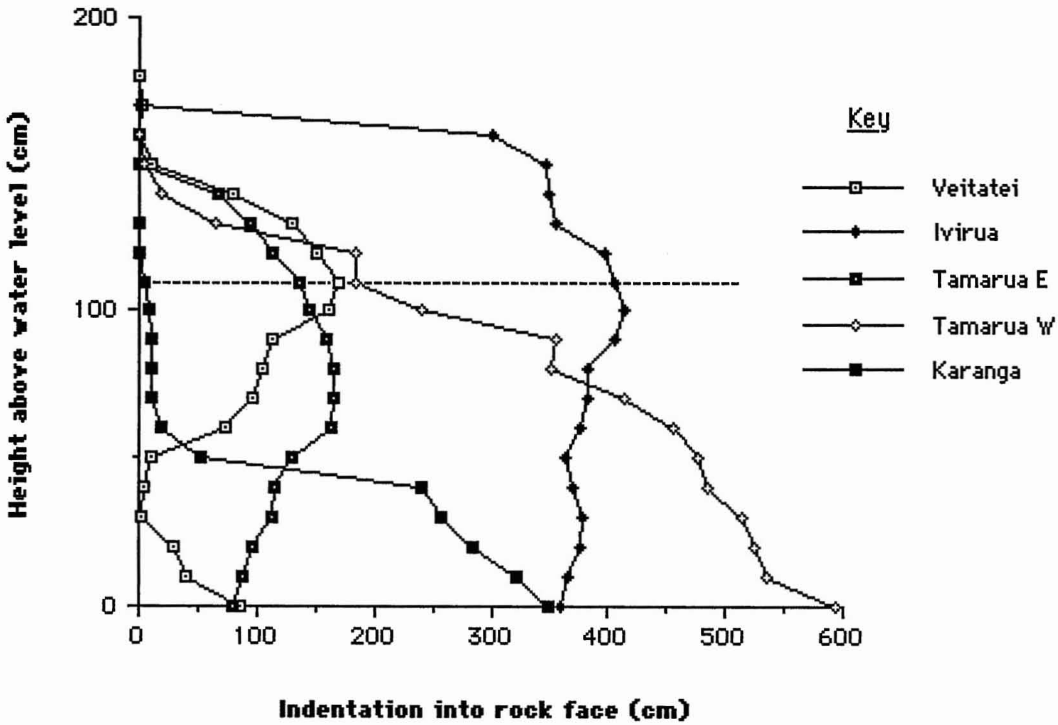


FIGURE 3. Morphology of raised lake notches, above the current water level, from five drainage basins.

Casuarina equisetifolia. At site 3, at the edge of a taro swamp, the vegetation assemblage is of *Hibiscus tiliaceus* and weeds, but the pollen assemblage is dominated by spores of *Pandanus tectorius*, presumably blown down from the makatea cliff above. At site 4, both vegetation and pollen assemblages are dominated by *Cyathea* sp. At site 5, there is high representation of spores of *Davallia solida* (Forst. f.), an epiphytic fern common on forest trees, and *Cyathea* sp. again is represented in the vegetation and pollen assemblages.

Fossil Pollen

Pollen diagrams from core VT6 at 600 to 1000 cm depth are shown in Figure 5*a* and *b*. Core VT6 was selected for pollen analysis because of its location in the western swamp tributary to Lake Tiriara. This is the swamp closest to the Tangatatau rock shelter (MAN-44), an archaeological site located under the inner makatea cliff (Steadman and Kirch 1990, Kirch et al. 1991, 1992). Results from VT6 can also be compared with the earlier pollen study from a Lake Tiriara core by Lamont (1990) and Kirch et al. (1992).

The pollen results from VT6 show two zones. Zone 1 is from 1000 to 850 cm depth, dated 3770 $\pm$ 100 to 2570 $\pm$ 90 yr B.P., and is dominated by pollen of trees: *Pandanus tectorius*, *Ficus* sp., Palmae (probably *Pritchardia* sp.), Malvaceae, *Guettarda speciosa* L., *Weinmannia samoensis*, *Cocos nucifera*, *Sophora tomentosa* L., *Erythrina* sp. (probably *E. variegata* L.), *Hernandia* sp. (either *H. moerenhoutiana* or *H. nymphaeifolia* [Presl] Kubitzki) and *Morinda citrifolia* L. (Figure 5*a*). Spores of forest ferns are also highly represented, such as *Asplenium nidus*, *Cyathea* sp., *Angiopteris longifolia*, and *Davallia solida*. Wetland indicators such as *Cyperus* sp. and also Gramineae are present and continuous through this period. Unexpectedly, *Rhizophora* sp.

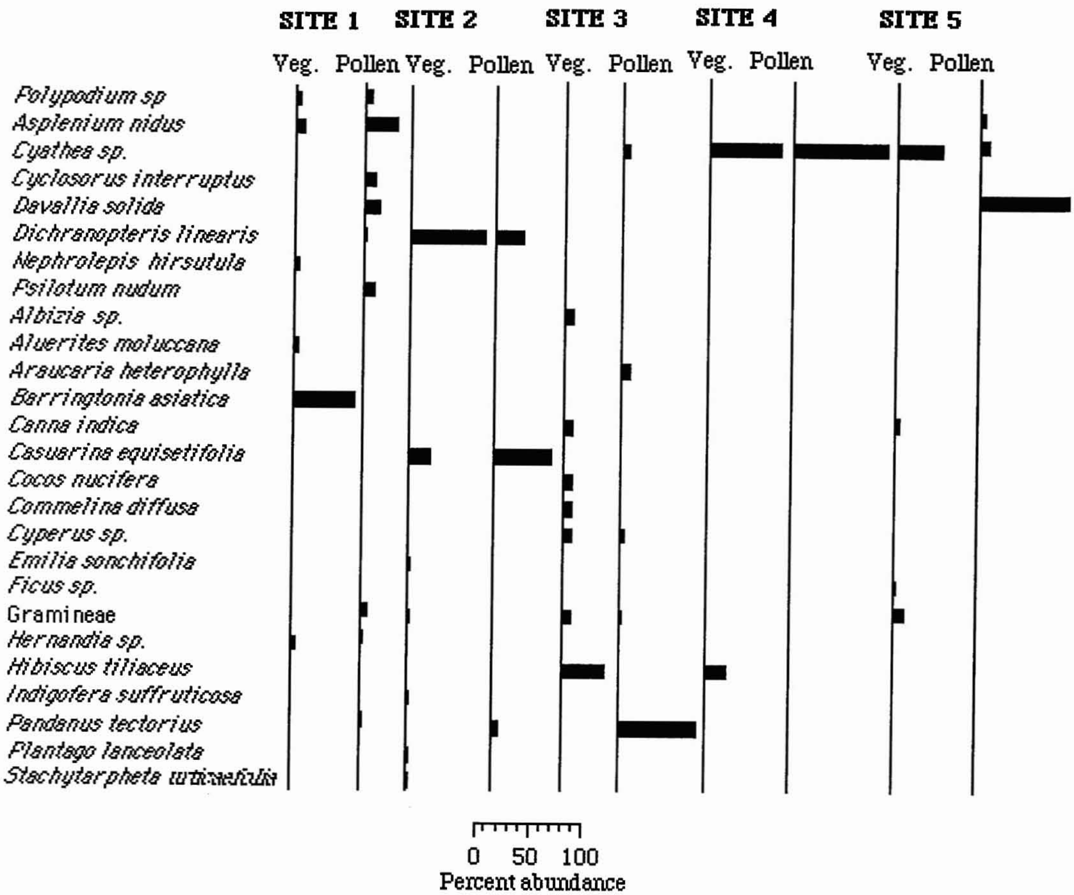


FIGURE 4. Percentage abundance of surface pollen assemblages and vegetation: site 1, outer makatea forest; site 2, central mountain summit; site 3, edge of taro swamp; sites 4 and 5, upland forest of Rarotonga.

pollen occurs consistently at 870, 840, and 800 cm depths, where it reaches a maximum concentration of 2691 grains/cm^3.

Zone 2 commences at 850 cm depth with a sudden decline in all forest species and dramatic increases in the fern *Dicranopteris linearis*, rising suddenly to 95,243 grains/cm^3, and 111,510 grains/cm^3 at 840 cm depth. Concentrations decline to 69,952 and 64,956 grains/cm^3 at 800 and 760 cm depths. Concentrations rise again at 720 cm depth to 104,525 grains/cm^3, and at that level there is a sudden and unsustained increase in Cyperaceae and Gramineae. Concentrations of *Dicranopteris* remain high to the 600-cm upper limit of pollen analysis. There is also an increase in the fern *Cyclosorus interruptus* (Willd.) H. throughout zone 2, which is a common plant on marshes (Whistler 1990). Concentrations are particularly high at the top of the zone (at 600 cm depth at the base of the clay deposit), corresponding with increase in the wetland fern *Acrostichum aureum* L.

Zone 2 is also characterized by the presence of microscopic charcoal fragments, which do not occur in zone 1 (Figure 5*b*). At 860 cm depth charcoal first appears with a concentration of 80,000 grains/cm^3 and rises between 840 and 640 cm depth to between 300,000 and 600,000 grains/cm^3. At 600 cm depth, the base of the clay deposit, concentrations of 170,000 grains/cm^3 were recorded.

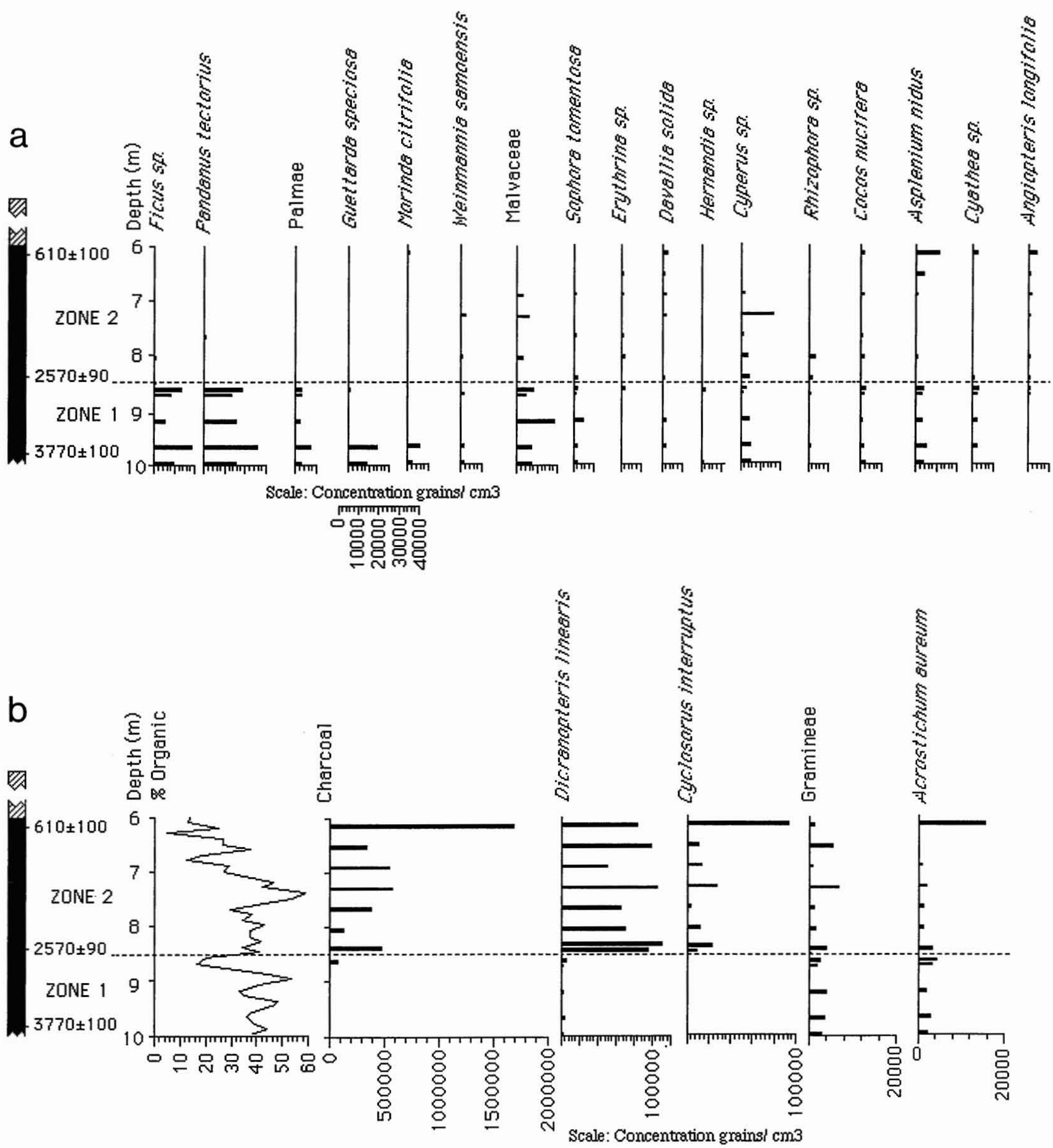
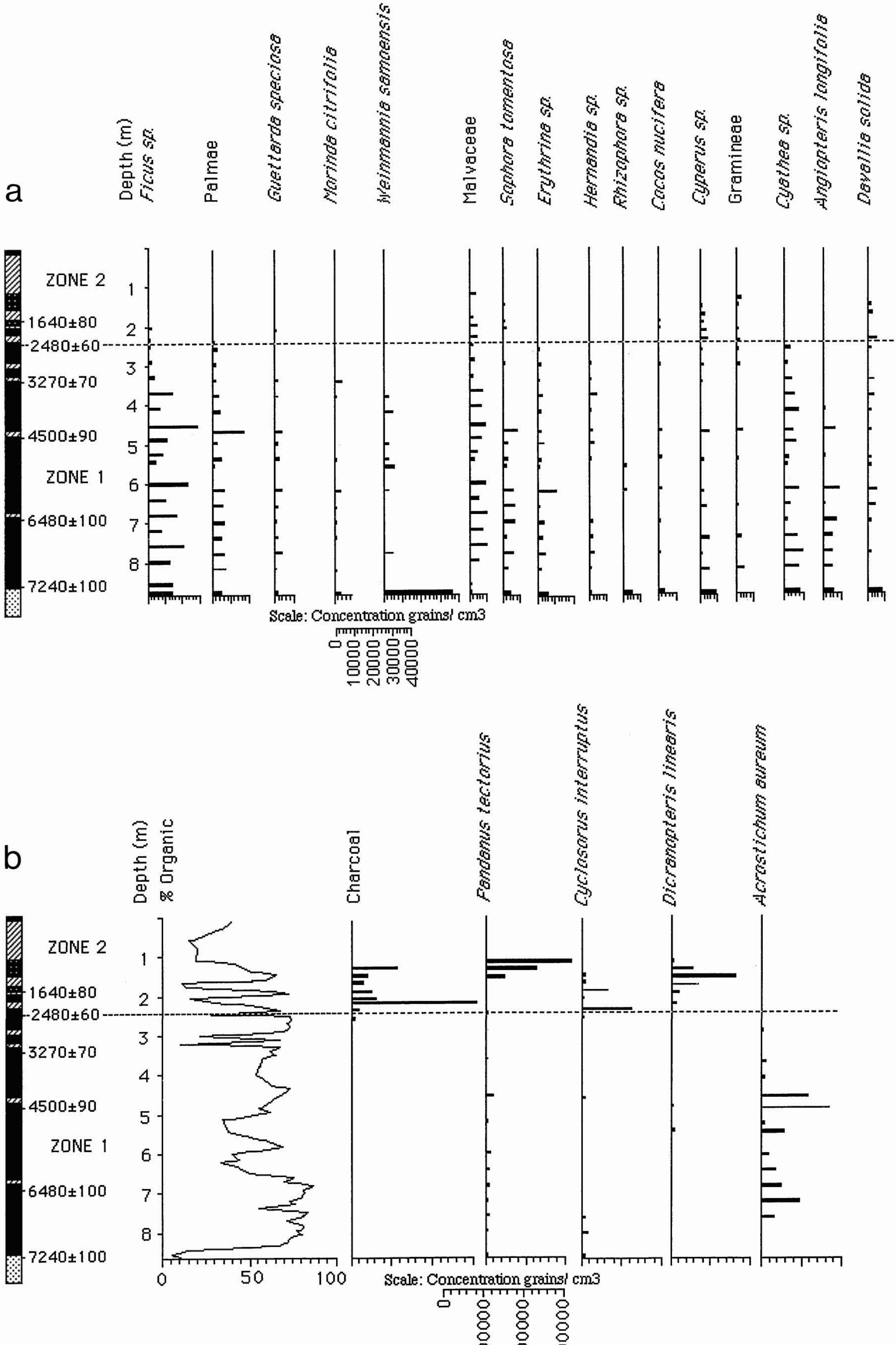


FIGURE 5. Pollen diagrams of core VT6, showing charcoal concentrations and percentage organic content of sediment in forest indicators (*a*) and in disturbance indicators (*b*).

Pollen diagrams from core TM7, 100 to 860 cm depth, are shown in Figure 6*a* and *b*. Core TM7 was selected for pollen analysis because it was extracted from the drainage basin closest to Veitatei, where the previous archaeological and palynological studies were carried out. Furthermore, this core has a complicated series of clay bands in its upper levels and allows detailed analysis of one of the four palaeo-lakes discovered in this study. It should be pointed out that this core extends back to 7240 yr B.P., whereas VT6 extends



a
Depth (m)
Ficus sp.
Palmae
Guettarda speciosa
Morinda citrifolia
Weinmannia samoensis
Malvaceae
Sophora tomentosa
Erythrina sp.
Hernandia sp.
Rhizophora sp.
Cocos nucifera
Cyperus sp.
Gramineae
Cyathea sp.
Angiopteris longifolia
Davallia solida
ZONE 2
ZONE 1
1640±80
2480±60
3270±70
4500±90
6480±100
7240±100
Scale: Concentration grains/ cm3
0
10000
20000
30000
40000
b
Depth (m)
% Organic
Charcoal
Pandanus tectorius
Cyclosorus interruptus
Dicranopteris linearis
Acrostichum aureum
ZONE 2
ZONE 1
1640±80
2480±60
3270±70
4500±90
6480±100
7240±100
0
50
100
Scale: Concentration grains/ cm3
0
100000
200000
300000

from 610 to 3770 yr B.P. The Lake Tiriara core examined by Lamont (1990) and Kirch et al. (1992) extends back to 6500 yr B.P.

The pollen diagrams of TM7 indicate two major zones. Zone 1 extends from the base of peat at 860 cm (7240 ± 100 yr B.P.) through most of the core to 240 cm depth (2480 ± 60 yr B.P.) and is dominated by forest pollen (Figure 6*a*). Fossil and spore assemblages are very similar to those in the VT6 zone 1 described above.

Events occur within the forest zone 1, but these do not disrupt the record of forest species sufficiently to designate a separate zone. At the base of the core at 860 and 850 cm a number of wetland species are represented: *Rhizophora* sp. with concentrations of 1413 grains/cm^3, *Cyclosorus interruptus*, Cyperaceae, and Gramineae. At depths of 540 to 450 cm, around the clay band and date of 4500 ± 90 yr B.P. there is higher representation of wetland species: *Rhizophora* sp., *Acrostichum aureum*, Cyperaceae, *Polygonum dichotomum* Bl., and *Cyclosorus interruptus*. There is also an increase in *Dicranopteris linearis*. The concentration of *Pandanus tectorius* doubles from previous levels.

Zone 2 of fossil pollen commences at 240 cm depth, dated to 2480 ± 60 yr B.P., with a large increase in the fern *Cyclosorus interruptus* to 4560 grains/cm^3 and *Dicranopteris linearis* to 1368 grains/cm^3. A clay band also occurs at that level. At 220 cm depth there is a dramatic decline in concentrations of forest species, including *Pandanus tectorius*, and increases in *Cyclosorus* (to 122,408 grains/cm^3) and *Dicranopteris* (to 13,696 grains/cm^3). *Acrostichum aureum* also increases. There is a date of 1640 ± 80 yr B.P. below a clay band at 180 cm, and at 170 cm *Dicranopteris* and *Cyclosorus* concentrations remain high and *Pandanus* and other forest species low. At 150 cm *Dicranopteris* increases to a concentration of 157,336 grains/cm^3, and *Cyclosorus* concentrations fall to 8864 grains/cm^3. Although concentrations of other forest species remain low or nonexistent, there is an increase in *Pandanus* from sustained levels of 2000 grains/cm^3 through the last meter to 49,860 grains/cm^3. At 130 cm *Dicranopteris* remains high and *Pandanus* concentrations increase, and at 110 cm depth *Pandanus* is dominant, with some *Dicranopteris* and *Asplenium*.

Zone 2 is also characterized by the presence of charcoal, which does not occur in zone 1 (Figure 6*b*). At 240 cm depth, dated to 2480 ± 60 yr B.P., charcoal first appears with a concentration of 10,000 grains/cm^3 and increases to 300,000 grains/cm^3 at 200 cm; this upper level corresponds with a clay band. Between 190 and 130 cm depth there are charcoal concentrations of between 25,000 and 60,000 grains/cm^3, and at 110 cm depth (the base of the clay deposit) concentrations rise to 113,000 grains/cm^3.

DISCUSSION

In the middle Holocene, five basins on Mangaia, Veitatei, Tamarua (W), Tamarua (E), Ivirua, and Karanga, featured lakes where the stream approached the inner edge of the makatea. Deep gyttja deposits from Veitatei show that this was the earliest lake to form, and dates from the base of deposits in the other four basins indicate that those lakes began to form between 7340 and 6370 yr B.P. Rapidly rising sea level caused flooding of the Pleistocene dry valleys. Pollen evidence from the base of core TM7 shows elevated concentrations of Cyperaceae and *Rhizophora* at the time of that flooding, indicating the creation of wetlands.

Two basins, Tamarua (E) and Ivirua, show a catchment disturbance between 6580 and 6380 yr B.P., with a clay lens in the gyttja. TM7 shows an increase in fern spores and can be compared with pollen results from Lake Tiriara of a decline in tree pollen and increase in clay content and fern pollen between 12 and 14 m, at 5750–6250 yr B.P. (Lamont 1990). From mineralogical study of the same core Dawson (1990) showed a coinciding increase in SiO_2, TiO_2, AlO_3, Fe_2O_3, ExtFe, and

FIGURE 6. Pollen diagram of core TM7, showing charcoal concentrations and percentage organic content of sediment in forest indicators (*a*) and in disturbance indicators (*b*).

residual FeO_3, indicating erosion of clays from the catchment. This disturbance could have been caused by a hurricane, which disrupted vegetation and induced soil erosion into the lakes, as posited by Lamont (1990). It could also have resulted from an El Niño Southern Oscillation (ENSO) similar to the one that caused drought, vegetation death, and soil erosion in 1982–1983.

The five basins with lake stratigraphy all have a solutional notch on the makatea wall around 1 m above the current water level (Figure 3). There is considerable horizontal extent of these notches, as at Veitatei and Tamarua (W) where it disappears at the swamp margins beneath soil deposits. This is interpreted as being a mid-Holocene lake solutional notch, indicating both the former extent of these lakes and the higher sea level at the time, shown by Yonekura et al. (1988) to be +1.3 m at 5000 yr B.P. and at a maximum level of +1.7 m at 4000–3400 yr B.P. on Mangaia. On the makatea wall behind Lake Tiriara a solutional notch occurs at the current level of the lake, and the fossil notch (as measured in three places) is 1.1 m above this. No notches occur higher, which indicates that the mid-Holocene high stand was sustained at 1.1 m; if sea level was higher, it was for an unsustained period. Lake Tiriara has an open conduit connection with the sea, shows small tidal fluctuations, and is slightly brackish (Dawson 1990), hence its water level is taken to be a sea-level indicator. The other lake notches correspond with this level, though the pattern can be obscured by lower development of an active conduit cave, as at Karanga and Tamarua (W).

Core TM7 from Tamarua (W) shows fine laminations in the lake peats between 665 and 455 cm, dated from 6480 ± 100 to 4500 ± 90 yr B.P. It seems likely that these fine laminations are annual and could be derived from annual algal growth on the lake bottom, with sufficient depth of the lake to limit bioturbation. This implies that through this period, from 6480 ± 100 to 4500 ± 90 yr B.P., the lake was probably at its deepest, with a combination of factors including a higher sea level and a lack of sediment infill.

At the upper margin of these laminations (from 540 to 450 cm, ca. 4500 ± 90 yr B.P.) the pollen diagram from TM7 shows high concentrations of wetland species such as *Rhizophora* sp., *Acrostichum aureum*, Cyperaceae, *Polygonum dichotomum*, *Cyclosorus interruptus*, and *Pandanus tectorius*. Because this does not occur in the earlier history of the lake, it is possible that this represents a slight sea-level fall, exposing shallow margins of the lake for colonization by wetland communities.

The two large drainage basins of Tava'enga and Keia have no corresponding lake stratigraphy or lake notch on the makatea wall because of their elevation, at 20–30 m above sea level.

The lakes were infilled in the later Holocene by deposition of gyttja, combined with sea-level fall and deposition of clay eroded from the catchment. With infilling, lakes shallowed to become reed swamps from the upper basins toward the lowest part at the makatea edge. This is indicated by the dates from Karanga where infill of the lake at the upper valley core KA3 was dated at 6260 ± 80 yr B.P., and infill at the lower valley core KA4 was at 2980 ± 80 yr B.P. Core TM4 indicates a transition from lake peat to reed swamp in the process of shallowing, dated at 4000 ± 70 yr B.P., indicating a falling sea level at that time; a similar stratigraphy is found in Ivirua. This is earlier than the 3400–2900 yr B.P. period of falling sea level found by Yonekura et al. (1988). Only one lake remains on Mangaia at the current time, Lake Tiriara in Veitatei, which reaches the lowest elevation of all catchments. Comparison between the 1974 topographic map and field survey in 1991 indicates that this lake also is infilling rapidly.

TM7 shows a catchment disturbance at 3270 ± 70 yr B.P., and VT6 shows a synchronous decline in the forest species of *Guettarda speciosa* and *Morinda citrifolia*. Like the 6500 yr B.P. disturbance described above, this could have been caused by a hurricane or an ENSO event. Wells (1990) showed a major ENSO event in northern coastal Peru from flood deposits dated at 3183 ± 61 and 3220 ± 130 yr B.P.

The swamp stratigraphy and both pollen diagrams indicate that the major Holocene environmental change on Mangaia can be attributed to the activities of the early Polynesians. The pollen diagrams reveal forest destruction and subsequent major clay deposition in the upper sequence of cores in all basins (Figure 2). This shows that the major areas of forest disturbance were on the central volcanic hill, resulting in severe soil erosion. As shown by charcoal occurrence, this was associated with fire, unlike the prehuman clay lenses.

Pollen analysis results from TM7 and VT6 indicate that the record of forest clearance occurs before major clay deposition. In TM7 *Dicranopteris linearis* and *Cyclosorus interruptus* ferns start to increase at 2480 ± 60 yr B.P., and *Dicranopteris* continues to increase until a major increase at 1640 ± 80 yr B.P. In VT6 increase of *Dicranopteris* occurs at 850 cm depth, dated at 2570 ± 90 yr B.P. Subsequently there is a decrease in *Dicranopteris* concentrations until 750 cm, indicating that earlier disturbance activities were intermittent, but after which high concentrations are sustained. Interpolating between the dates in VT6, this is between 1593 and 1668 yr B.P. Dates on peat below major clay deposition are 1930 ± 60 yr B.P. from Ivirua and 1830 ± 80 yr B.P. from the eastern branch of Veitatei.

Both cores indicate some human activity on Mangaia as early as 2500 yr B.P., as shown by pollen records of forest disturbance and associated charcoal deposition. The weighted average of the dates on early human disturbance of 2480 ± 60 from TM7 and 2570 ± 90 from VT6 is 2507 ± 50 cal B.P. (using Stuiver and Reimer 1986). Lamont (1990) showed a decline in tree pollen and appearance of weeds between 6 and 5 m depth in Lake Tiriara, dated at 3000 to 2700 yr B.P. Major disturbance is shown from that study around 1600 yr B.P. The research reported here also indicates that systematic island-wide disturbance occurred about the same time, around 1650 yr B.P., as shown from major and sustained increase in *Dicranopteris* ferns in both TM7 and VT6.

Relating this record to possible human activities, small numbers of people may have arrived around 2500 B.P., maintaining interisland exchange and perhaps not permanently settling the island. A low, temporary population would have left little archaeological record, but some burning and clearance of forest occurred. Over time, population increased and interisland exchange declined; consequently the island's resources became more heavily exploited. Development of this later "open society" has been shown from Easter Island, the Marquesas, and Fiji to be associated with environmental disturbance (Suggs 1961, Flenley and King 1984, Kirch 1984, Southern 1986). In Mangaia, major environmental disturbance commenced around 1900–1800 yr B.P., as shown by clay deposition, but widespread clearance of vegetation on the central cone did not occur until about 1650 yr B.P. The date of 610 ± 100 yr B.P. below 620 cm of clay at VT6 indicates a point in a trend of continuing infill of Lake Tiriara in Veitatei.

Fossil pollen concentrations indicate that a number of species are native on Mangaia that either are not there currently or were not previously thought to be native. These include the wetland fern *Acrostichum aureum*, the mangrove *Rhizophora* sp., and the economically significant trees *Morinda citrifolia* and *Cocos nucifera*. The coconut has now been found to have occurred before human arrival in Melanesia (Hossfeld 1965, Spriggs 1984), and the occurrence here in Polynesia indicates that natural dispersal of the progenitor to the cultivated *Cocos nucifera* enabled it to have a wider distribution than was earlier thought. *Rhizophora* was not previously believed to be indigenous east of Samoa (Ellison 1991) and seems to have colonized the inner swamps of Mangaia through the conduit caves, which would have been more open in the earlier Holocene before later clay infill (Ellison in press). The loss of *Rhizophora* from Mangaia shown in the pollen diagrams could have been caused by decreasing salinity of the inner swamps as sea level fell and the conduit caves closed up. *Casuarina equisetifolia* is not native, rather being shown to be a relatively late Polynesian introduction. Surface sample 2 showed high pollen representation from *Casuarina*, yet its pollen does not occur at all in the fossil record.

It must be remembered that pollen diagrams preferentially record species that are wind-pollinated. The surface pollen study indicates that a number of species can be heavily present in the modern vegetation assemblage and yet not occur at all in the pollen/spore deposition assemblage. Examples are forest trees such as *Barringtonia asiatica* and *Hibiscus tiliaceus*. Surface sample site 3 shows how high-pollen-producing species such as *Pandanus* can dominate the pollen record of a location where *Pandanus* is not actually growing. However, although questions of ecological change within a forest are difficult to address because many species do not occur in the pollen record, indicator species can be used to demonstrate external forcing factors on the vegetation assemblage such as changes in hydrological regime and human impact.

CONCLUSIONS

The most important Holocene environmental change on Mangaia was caused by the early Polynesians, as indicated by the stratigraphy of 21 swamp cores and by pollen analysis of two of these cores. The pollen diagrams and charcoal concentrations indicate an early phase of human colonization, from ca. 2500 yr B.P., with limited forest clearance. Major forest destruction occurred at ca. 1650 yr B.P., coinciding with major clay deposition as seen in the upper sequence of cores in all basins. This indicates that the primary areas of forest disturbance were on the central volcanic hill, resulting in severe soil erosion. This led to the infilling of the five lakes that had been present from the mid-Holocene.

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